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Status Report #6

Subcooled Boiling in a Negligible Gravity Field

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I. INTRODUCTION

This status report is concerned with a research program sponsored by the National Aeronautics and Space Administration with technical liaison handled by Lewis Laboratory in Cleveland. The original objective of the research program was to investigate the bubble mechanics and heat transfer aspects of liquids boiling under subcooled conditions while subjected to a negligible gravity environment. At the suggestion of the NASA Technical Monitor, Mr. Otto, the primary emphasis of the program is currently being placed on obtaining radius-time relations under normal gravity conditions. The effects of the negligible gravity environment will be investigated at a later date when the normal gravity situation is well defined.

II. STATUS OF TECHNICAL WORK

The work on this project since the last report (November, 1963) has consisted primarily of performing the necessary modifications to the boiler and supporting instrumentation needed to supply the best possible laboratory data. Many of these modifications are of such a nature that they will be of no use in later zero-gravity studies but do improve the quality of the laboratory experiments considerably. During the latter weeks of this reporting period, a significant number of experimental data runs have been made and analyzed. This work will be described in the following paragraphs.

Equipment Modifications

There have been no modifications made to the heating element or heating jig since the last report. However, there was evidence that the bubbles were touching the mirror at low subcoolings and high heat fluxes. Therefore, the gold mirror was moved back approximately 1/16 inch from the heating surface to allow a better view of the heating surface and base of the bubble.

The boiler was modified to allow a larger field of view of the heating surface. This was accomplished by making a new lens holder and lid which allowed a 2-inch extension of the boiler. The quality of photographic data obtained was significantly improved by this step. After a number of data runs to properly focus the lens with the camera, the boiler was sealed and equipped with a condenser system to prevent loss of water during test runs.

Since the primary objective of the research program now is to obtain good laboratory data, the lighting system for the camera was modified. Earlier designs had to be incorporated into the drop package and placed severe power and space restrictions on the lighting system which are not a prerequisite in the laboratory. A system of commercial flood lamps and "sunguns" are being used at the present with satisfactory results.

The bulk temperature measurement is being accomplished with a set of 30 gauge iron-constantan thermocouple probes placed at $\frac{1}{2}$ and $4\frac{1}{2}$ inches above the heating surface. These probes are being monitored with a dual channel potentiometer employing an ice bath reference junction.

Experimental Test Runs

At the time of this report a total of 27 test runs of the system have been completed. Of these, twenty were at a heat flux of 80,000 BTU/HR-FT^2 and seven were at a heat flux of 50,000 BTU/HR FT^2. Only nine test runs at the 80,000 heat flux produced photographic data of a usuable nature due to the extremely sensitive nature of the lens system to lighting and focusing. All of the runs made at 50,000 BTU/HR FT^2 are of usable quality and are progressively better due to improved focusing and lighting techniques.

These test runs cover a range of bulk temperatures from 202°F to 160°F. The test runs made near saturation temperature do not produce usable photographic data. As the bubbles leave the surface at low degrees of subcooling they tend to collect on the lens which is positioned directly above the heating surface. However, as the subcooling increases, this is no longer a problem and the condensing bubbles do not collect on the lens.

A maximum framing rate of 7800 frames per second is being achieved. However, bubbles suitable for analysis are not always obtained during the short period of time in which the camera is at maximum framing rate. Each roll of film produces from zero to four bubbles suitable for analysis, depending upon adjacent bubbles which often interfere with the growth pattern of each other.

Data Analysis

Investigation of the photographic records indicate that there are at least three types of bubbles or bubble patterns present during the boiling process: (1) Oscillating Bubbles - this type of bubble is generally small and its point of nucleation is a very active site. The bubble is first evident as a very small point of light appearing in the vertical view mirror. The bubble oscillates at a very high frequency in both an expanding and contracting mode and also in a horizontal mode. Many of these bubbles grow in a gradual manner with the bubble contracting less than it had expanded. After a number of oscillations and the resulting growth, some of the bubbles will separate from the surface and be condensed. Sufficient data is not yet available to attempt an analysis of this phenomena in a quantitative sense.

(2) Continuous growth and decay bubbles - this type of bubble does not exhibit the oscillating motion previously described. The bubble, when first evident on the film, has achieved 1/5 to 1/3 of its final diameter. The bubbles continues to grow at a diminishing rate until it reaches a maximum diameter in the plan view and then begins to condense at a much slower rate. Some of this type of bubbles separate from the surface after experiencing a necking-down process which occurs a considerable time after the maximum plan view diameter is reached.

(3) Multiple bubble groups - this type of bubble groups contain both the oscillating and the continuous growth types but appear to nucleate in groups of two or more simultaneously. The heating surface will often lie void for considerable periods of time without nucleating a single bubble and then two or more bubbles will appear simultaneously and immediately begin to attract each other. Upon combining, they separate from the surface quite violently and experience considerable distortion during the condensing process. Due to the extremely irregular surface and unconventional action of the bubbles, the evidence of this type of bubble groups has not been sufficient to allow a quantitative approach to the processes involved.

A quantitative analysis has been attempted on the continuous growth and decay type tubble. This approach is based upon assuming that the bubble can be analyzed as a sphere with a mean diameter equivalent to the average of the three axes. These three distances are measured from the film records after magnifying the image approximately sixty times. This mean diameter is then plotted as a function of time. This diameter versus time curve is then differentiated twice to give the velocity ($\dot{R}$) curve and the acceleration ($\ddot{R}$) curve.

Figure 1 is a proposed radius-time curve for this type of continuous growth and decay type bubble. The velocity and acceleration curves are also shown on the figure. Only a small portion of the total curve can be witnessed in the photographic records due to the limitations of the camera framing rates and the tendency of the bubble to distort and move out of focus after detachment.

Region (1) is the initial growth period contained within the nucleating site. In this stage of growth the bubble is not visible and the time required to complete this stage is unknown but should not be over a few microseconds in duration.

Region (2) is the initial expansion stage of growth and is very dynamic in nature. The elapsed time for this region is less than 130 microseconds, one camera frame, and the mean diameter of the bubble has obtained 1/5 to 1/3 of its final maximum value at the end of this period. The bubble is not visibly witnessed until it has entered Region (3) marked by the line 0-0'. This region is the final expansion and decay portion of the bubble cycle. Approximately twenty bubbles have been analyzed and plotted in this manner and all exhibit the same general curve shape and magnitudes.

The magnitude of the velocity curve upon entering Region (3) has decayed to 50-400 cm/second for the cycles studied. The acceleration curve has decayed to a deceleration of 200,000-2,000,000 cm/sec^2 for these same cycles. All of the bubble cycles studied so far indicate that both of these curves have passed their inflection points prior to entering the visible region. If this deduction is valid, the momentum and inertia forces present in region (2) must be several orders of magnitude greater than the ones witnessed in Region (3).

Figure 2 is a plot of maximum mean diameter versus degree of subcooling. This figure indicates that there seems to be some relation between subcooling and maximum mean diameter, and also between heat flux and maximum mean diameter. However, it should be said that bubbles of all shapes and sizes exist for every subcooling and heat flux and if a true relation of these variables exists it will have to be defined in a statistical average based on a large number of bubbles at every value of heat flux and subcooling. The bubbles studied and plotted in Figure 2 were picked entirely at random and no attempt was directed towards size distribution.

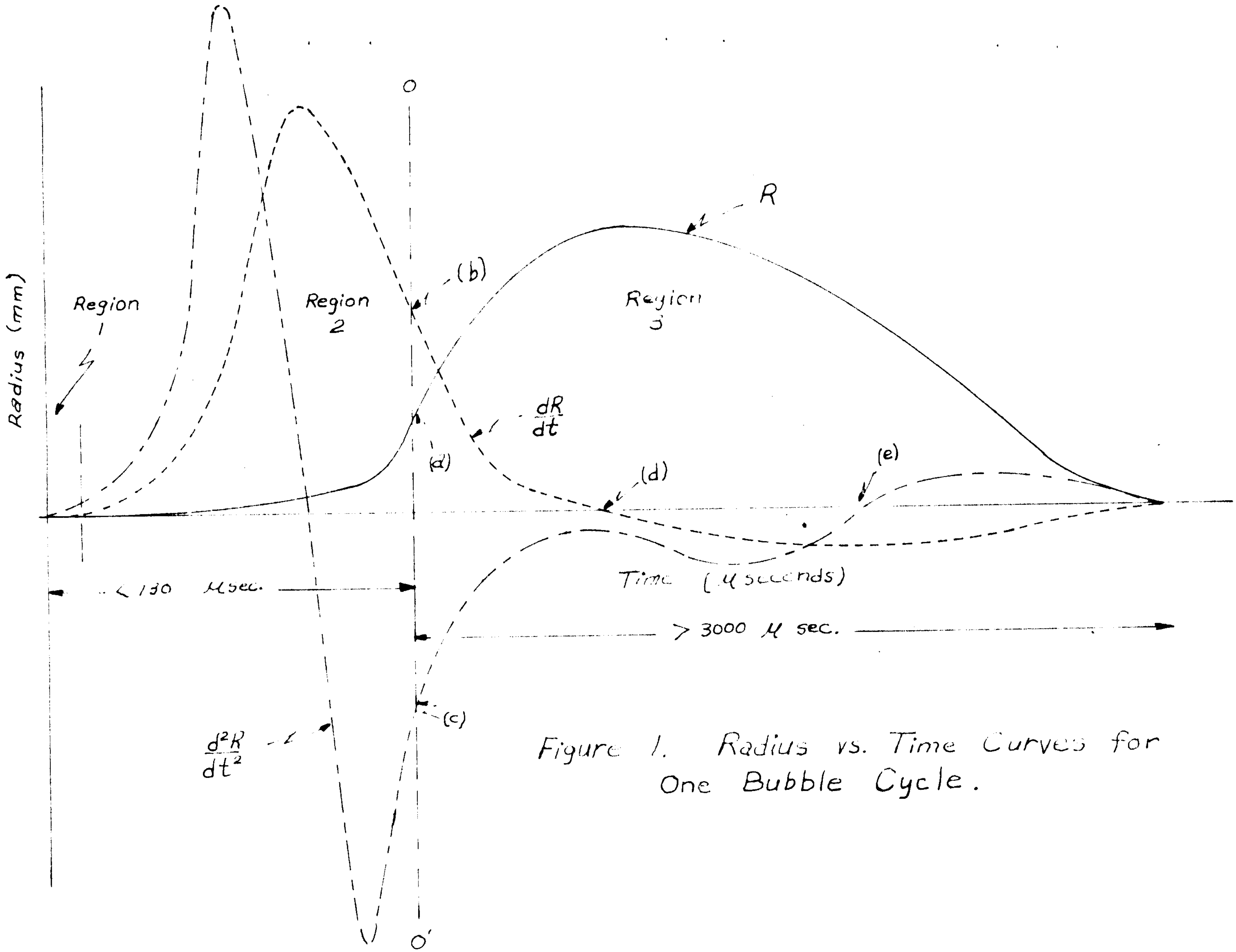

Figure 1. Radius vs. Time Curves for One Bubble Cycle.

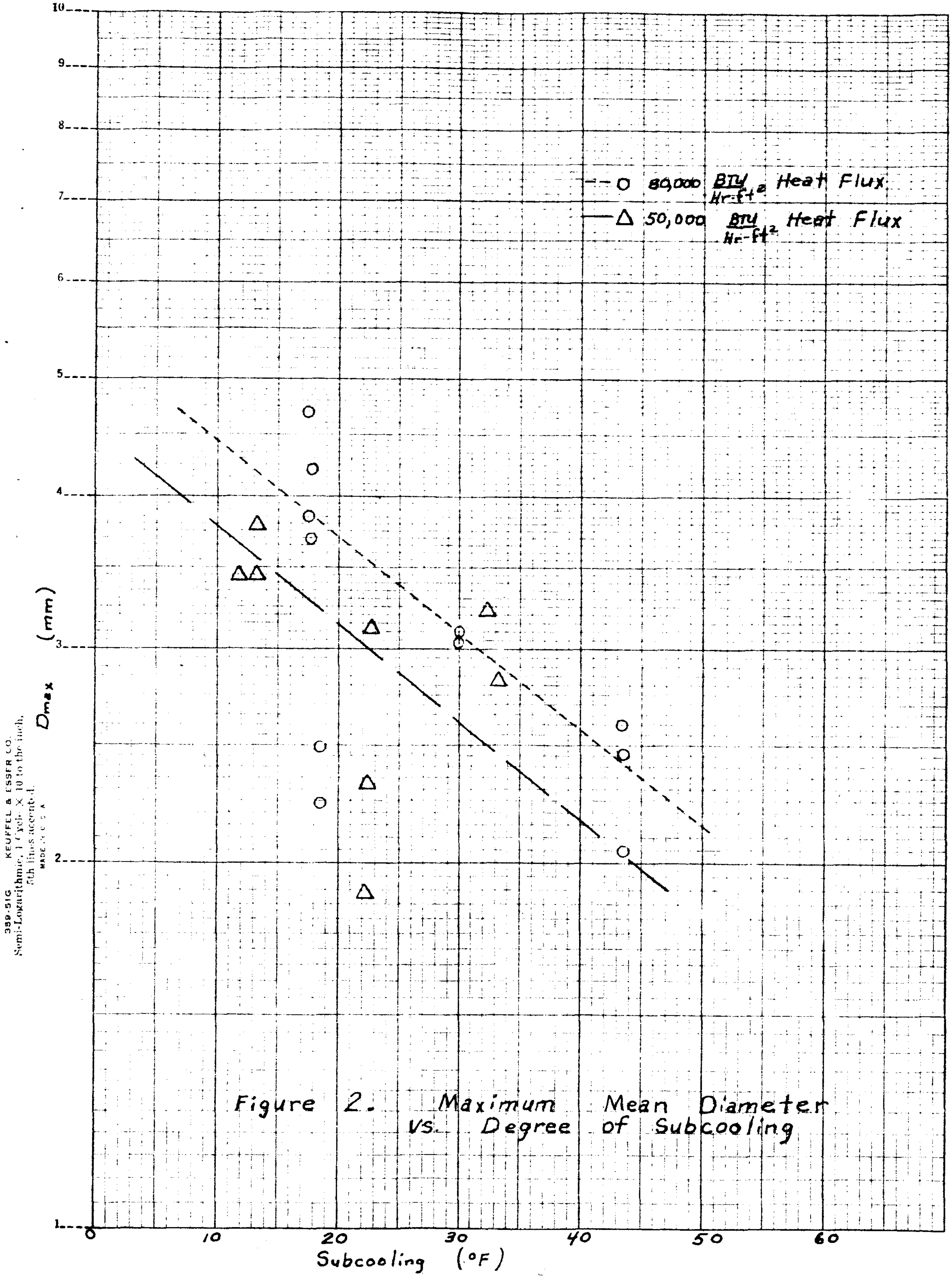

Figure 2. Maximum Mean Diameter vs. Degree of Subcooling

Due to the limited data available and the inability of the camera system to record the growth characteristics of Region (2), no general relationship has been found between the degree of subcooling and velocity or acceleration. A relation of this sort would be extremely difficult to define until a common point in the growth cycle can be located.

The above discussion of a bubble cycle has been based on observed data and analyzed on the assumption that a bubble can be considered a spherical model. This assumption leads to inconsistencies which cannot be reconciled with the actual growth, decay, and separation of a bubble in a subcooled boiling process. The object of this research program is to find a relation of the buoyant forces to the inertia forces in the form of a modified Froude Number. It was originally assumed that a bubble could be expressed as a sphere with a mean diameter based on the three dimensions of the bubble and that separation would occur at R_{max}. Experimental evidence indicates that both of these assumptions are invalid and do not define the dynamics involved.

Bubbles encountered in subcooled boiling are not spherical during their growth and decay phases. They only approach a general spherical shape during the early portion of their lives when they are very small and they tend towards a spherical shape after they have separated from the surface and are tending towards the shape of a minimum volume, i.e., a sphere.

Experimental data indicates that bubbles generally have an axial arrangement of the tetragonal type during its growth and decay phases, i.e., two equal and one shorter axis and all at 90° to each other. The bubbles are generally of a truncated spherical shape when very small. This can be witnessed by the observation of the small oscillator type bubbles. They tend to oscillate very little in the vertical direction until they have attained an increased volume. As a bubble continues to grow the ratio of the (a-a) axes to the vertical axis, b, approaches 2/1. This ratio persists until the (a-a) axes reaches a maximum. At this time the vertical axis continues to grow and the (a-a) axes begin to diminish. This process is continued until all three axes are approximately equal at which time a necking-down process begins a small distance above the heating surface. The bubble is eventually separated from the surface but this separation does not take place during the growth dynamics of the plan view diameter. This separation takes place long after the plan view diameter of the bubble has reached a maximum and does not appear to be a highly dynamic process.

These points may be summarized as follows:

(1) A bubble cannot be adequately described and analyzed as a sphere or an equivalent spherical volume. The bubble shape, and therefore the volume, is a function of time and must be treated as a point value.

(2) Bubbles do not separate at R_{max}, i.e., $(\frac{a + a + b}{3})$ or $(a \cdot a \cdot b)^{1/3}$ but only when $b \geqq a$.

(3) If the heat transfer out of the bubble interface is equal to or greater than the heat transfer into the bubble from the surface and superheat layer, the bubble will not separate. It will become stagnant, begin to condense, or become an oscillator type bubble.

Taking these findings into account, it seems reasonable to assume that any analytical approach to the bubble mechanics using a spherical model incorporates inherent inconsistencies which cannot be accounted for. For this reason it is necessary to perform a more rigorous analysis of each bubble on a volume and shape basis. The following force equations are proposed as a means of accomplishing this analysis:

Bouyant Forces

Without exception the experimental data obtained in the program has indicated that the bubble shape in the plan view is circular within experimental error. Therefore, the controlling dimension in the bubble cycle is the vertical height above the heating surface and the corresponding bubble shape in the vertical profile. If we let V_b equal the bubble volume at any time it can be determined graphically from the vertical profile.

The bouyant force results from the difference of the density of the vapor and the liquid volume it displaces. For any shape bubble this expression is:

$$F_B = \frac{g}{g_c} V_b \left(\rho_v - \rho_L \right) \qquad (1)$$

Since the vapor density is several orders of magnitude less than the density of the liquid, it may be neglected and the equation reduces to:

$$F_B = -\frac{g}{g_c} \rho_L V_b \qquad (2)$$

the minus sign indicates that the bouyant force is directed opposite to the gravity field which is a negative quantity.

Inertia Forces

The growing bubble establishes a flow field in the surrounding liquid. This flow field is directed in all directions away from the heating surface during the growth phase of the bubble. However, the bubble is basically symmetrical about the vertical axis and the only net inertia force acting on the bubble will be directed away from the heating surface.

The bubble induced inertia force is equal to the time rate of change of momentum, i.e.

$$F_D = \frac{1}{g_c} \frac{d}{dt}(m v) \tag{3}$$

where m is the apparent mass of the liquid put into motion and v is the mass center velocity.

$$m = V_b \rho_L$$

$$v = U_b \tag{4}$$

Then by substituting:

$$F_D = \frac{\rho_L}{g_c} \frac{d}{dt}\left(V_b U_b \right) \tag{5}$$

Differentiating with respect to time yields:

$$F_D = \frac{\rho_L}{g_c} \left[U_b \frac{dV_b}{dt} + V_b \frac{dU_b}{dt} \right] \tag{6}$$

or

$$F_D = \frac{\rho_L}{g_c} \left[U_b \dot{V}_b + V_b \dot{U}_b \right] \tag{7}$$

This equation is a general equation for inertia forces and is valid at any time in the bubble life cycle. The variables V_b and U_b are point functions directly related to bubble shape and therefore functions of time.

The volume versus time and center of mass versus time curves will have to be derived from the high speed photographic records and calculated graphically from each frame. Although this method is considerably more rigorous and demanding, it should produce data which more nearly fits the actual process.

Analytical Procedures

Since both the viscous and surface tension forces are directed towards the heating surface and tend to retard or prevent separation, they can be neglected from this study of separation causing forces.

The Froude Number is a dimensionless ratio expressing the relationship of the inertial forces to the bouyant forces (i.e. gravity in this case). Using a modified form of this expression to compare these flow fields yields:

$$\psi_F = \frac{F_D}{F_B} = \frac{\frac{\rho_L}{g_c}\left[U_b \dot{V}_b + V_b \dot{U}_b\right]}{-\frac{g}{g_c}\rho_L V_b} \qquad (8)$$

or reduced to:

$$\psi_F = -\frac{1}{g V_b}\left[U_b \dot{V}_b + V_b \dot{U}_b\right] \qquad (9)$$

From this expression it can be seen that as zero-gravity is approached, the ψ factor becomes infinitely large. However, to effect separation, the inertia forces must still exceed the surface tension and viscous forces tending to hold the bubble to the surface.

Heat Transfer Data

Primary emphasis has been placed on the bubble dynamic aspect of the program during this initial series of test runs. However, a significant amount of heat transfer data has been recorded and analyzed at the two heat fluxes covered by this report. Figure 3 is a plot of heat flux versus bulk liquid temperatures. This figure illustrates the extent to which the test series has covered the ranges of subcooling.

Figure 4 is a plot of the overall heat transfer coefficient (U_T) versus the degree of subcooling. The data indicates a general trend of the coefficient increasing with a decrease in subcooling for a constant heat flux. This trend is what would be expected in the nucleate boiling region. However, it is also evident that considerable data scattering is being obtained. This inconsistency is a result of wide variations in surface temperature obtained at a constant heat flux and subcooling. It has not been determined whether this variation is caused by the nucleating process or is due to instrumentation defects. Further efforts will be made to determine the cause of this discrepancy in future test runs.

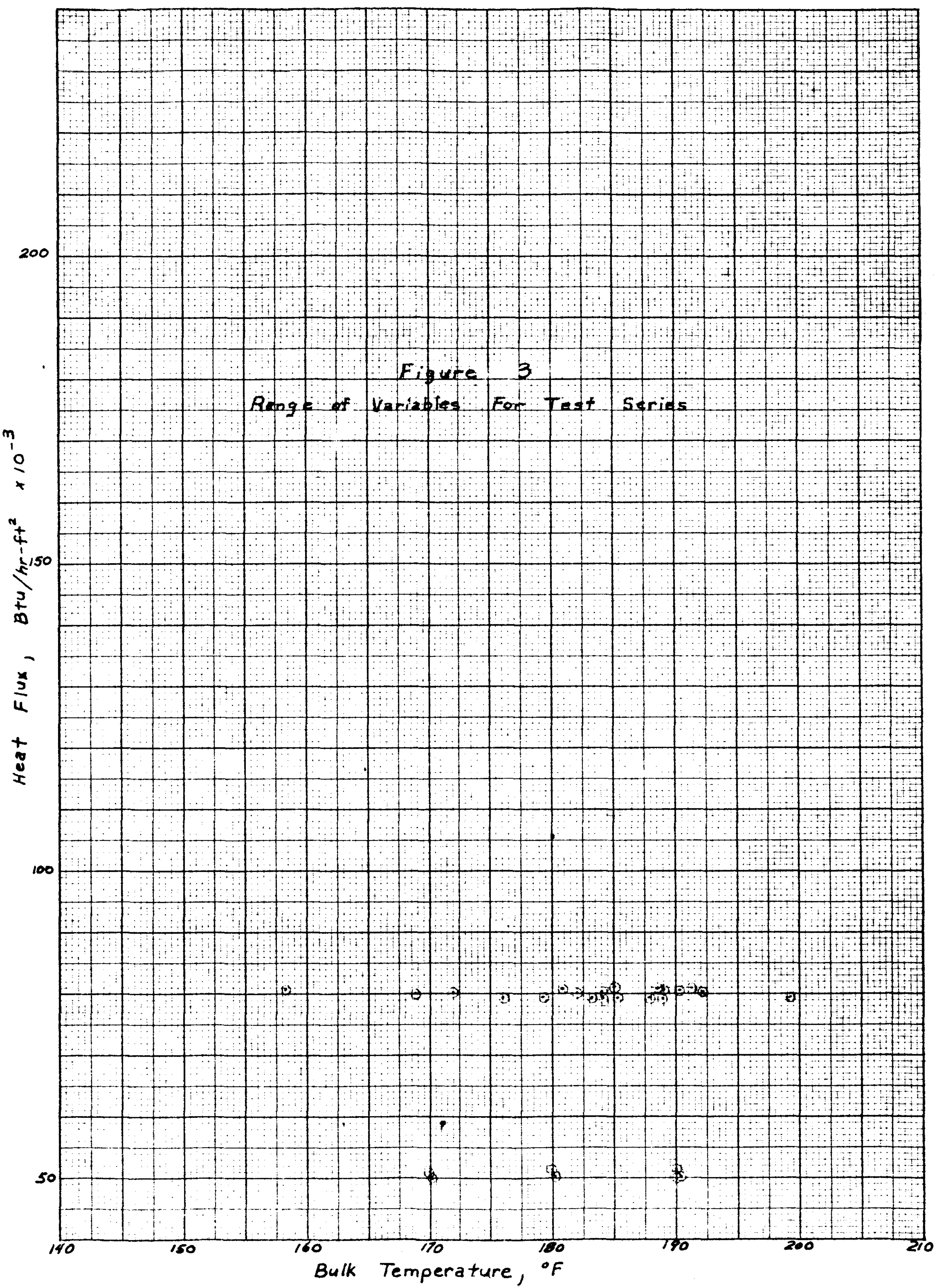

Figure 3

Range of Variables For Test Series

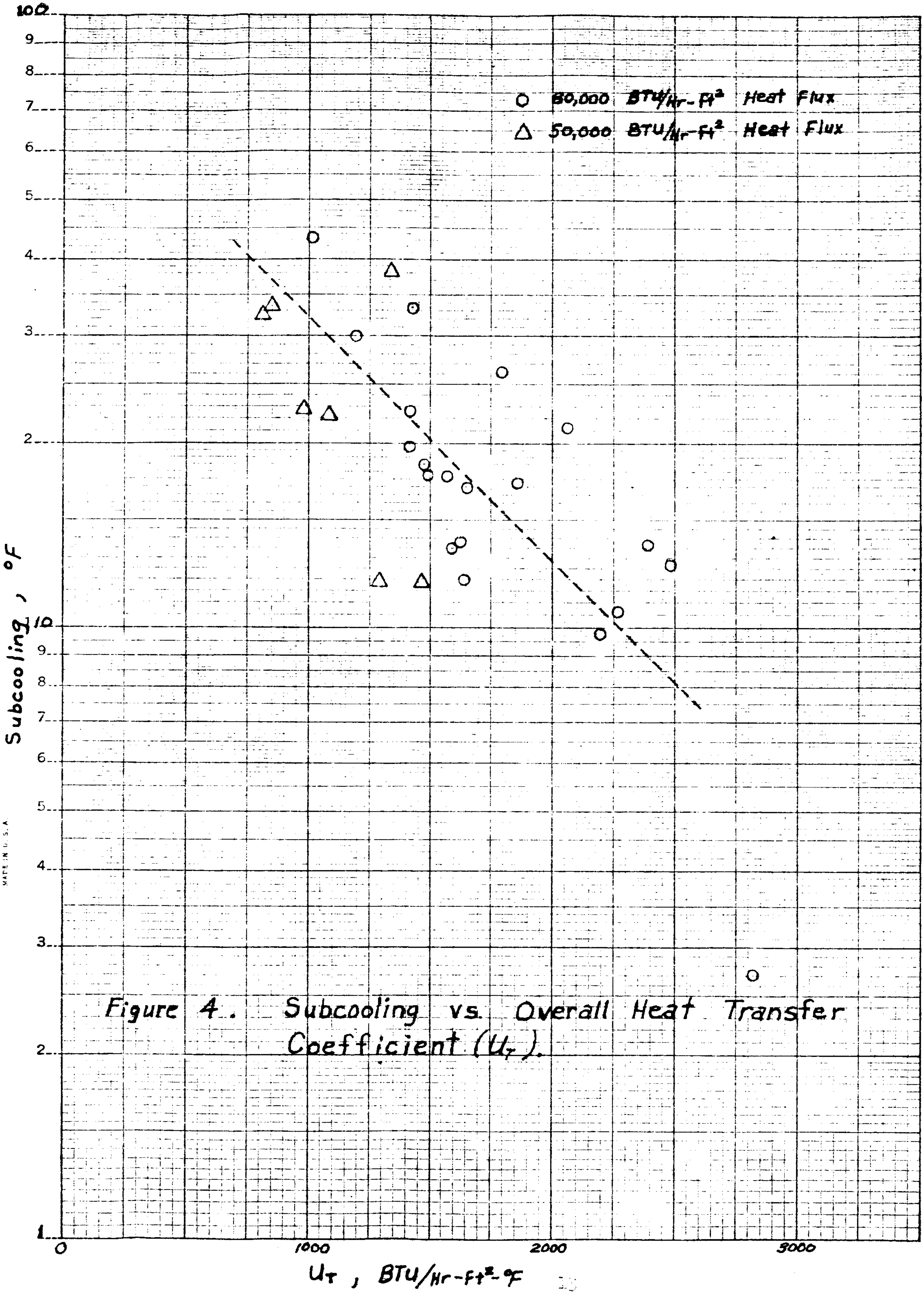

Figure 4. Subcooling vs. Overall Heat Transfer Coefficient (U_T).

III. PROPOSED FUTURE PROGRESS

Further experimental studies will be conducted in several other heat flux ranges and with a wider range of subcooling at each flux. The majority of these runs will be conducted at heat fluxes in excess of 100,000 $BTU/HR\text{-}FT^2$ due to the difficulty of maintaining consistent boiling at fluxes less than 50,000 $BTU/HR\text{-}FT^2$.

As a result of the experimental findings described earlier in this report, it has been decided that the camera system should be modified to allow vertical profiles of the bubble to be recorded. This can be accomplished by placing the camera in a horizontal position and filming the bubble against a contrasting background. This position will produce the vertical profile of the bubble directly and as a result of the placement the bubble will remain in the focusing plane of the camera during its entire cycle. The plan view diameter will be measured from the vertical profile and as mentioned earlier, this plan view has consistently been circular in shape.

Since the inertia and momentum forces involved in the growth phase of the bubble are primarily developed in the first 130 microseconds or less of the bubble life, it would seem advisable to make an attempt to define the magnitude of these forces. This can only be accomplished by employing a camera with sufficient framing rate to record this early radius vs. time relationship. It is estimated that a framing rate of at least 100,000 frames per second would be required to give sufficient data in this area. However, this requirement is well beyond the capabilities of the system being used, although the use of any camera giving framing rates above 8,000 frames per second would be helpful.